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Deep Space Acquisition, Tracking, Pointing (ATP) Technologies for Optical Communication

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Outline



- Background
- Pointing Accuracy Requirements
- Status of Current ATP System performance
- Approaches
- Acquisition, Tracking, Pointing Technologies
- Technology Developments
- Summary



Benefits and Challenges of Optical Communication



Benefits

- High data rate
- Small, lightweight terminals
- Low power
- EMI insensitive

Challenges

- Accurate beam pointing
- Background light sources
 >>Sun, Moon, Planets
- Optical alignments
- Atmospheric attenuation



Optical Comm Background



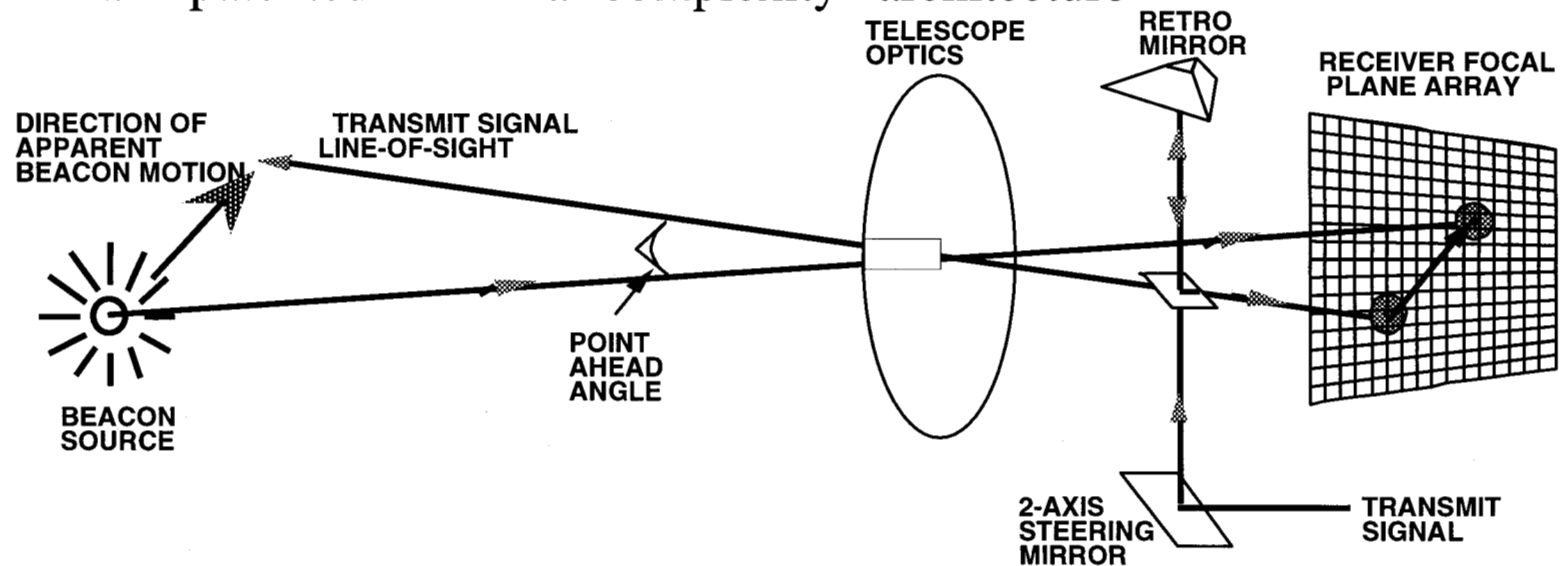
- JPL program started in 1979
- Includes spacecraft and ground technologies, systems, infusion planning, and system-level demonstrations
- Developed an Optical Comm. Demonstrator (OCD)
 - Laboratory-qualified functional model of a flight terminal
- Conducted a number of system-level demos
- Installing an Opt. Comm. Telescope Lab. (OCTL)
- Technology applies to multiple NASA Enterprise themes (HEDS, SSE, ESE, SEU, ASO)
- JPL has responsibility for all NASA applications of optical comm

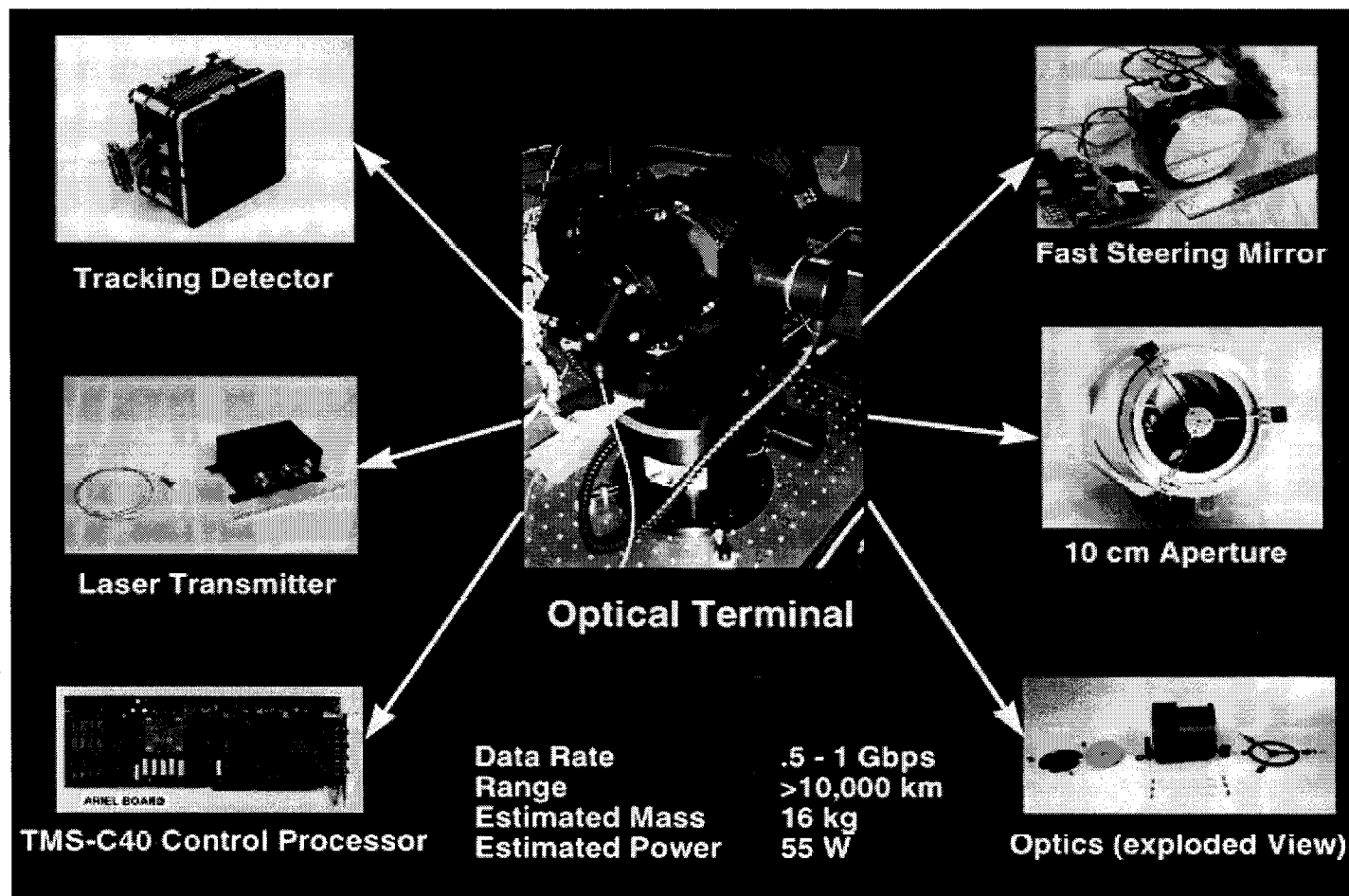


Opt Comm Demonstrator Concept



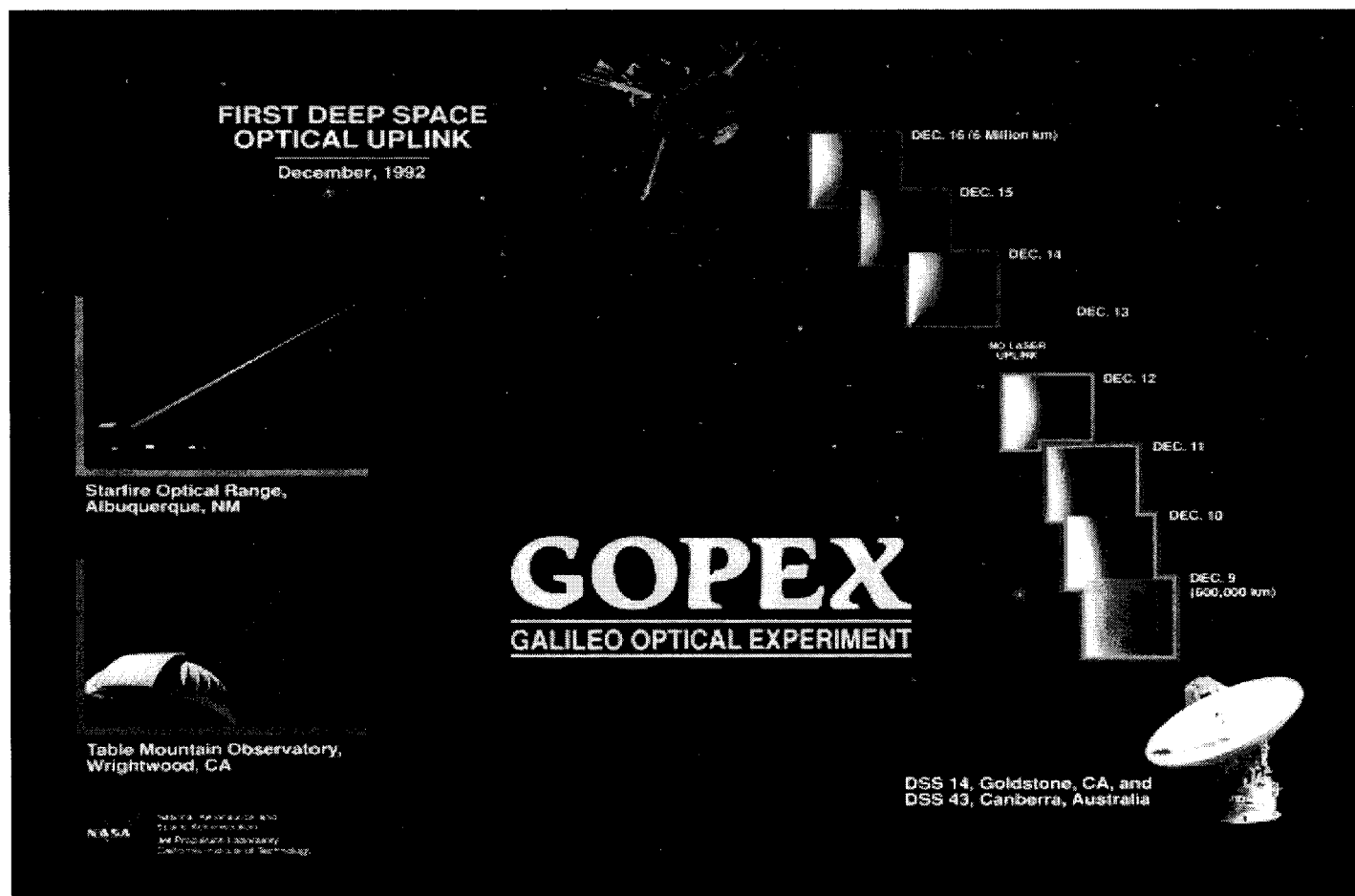
- Uses single steering mirror and single tracking detector array to accomplish beacon acquisition, tracking, XMT/RCV co-alignment, and transmit-beam point-ahead
- Fiber-coupled laser transmitter removes heat from optics area
- NASA-patented “minimal-complexity” architecture





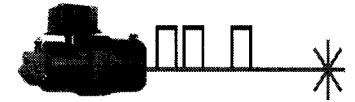


Past Opt. Comm. Demonstrations





Past Opt. Comm. Demonstrations

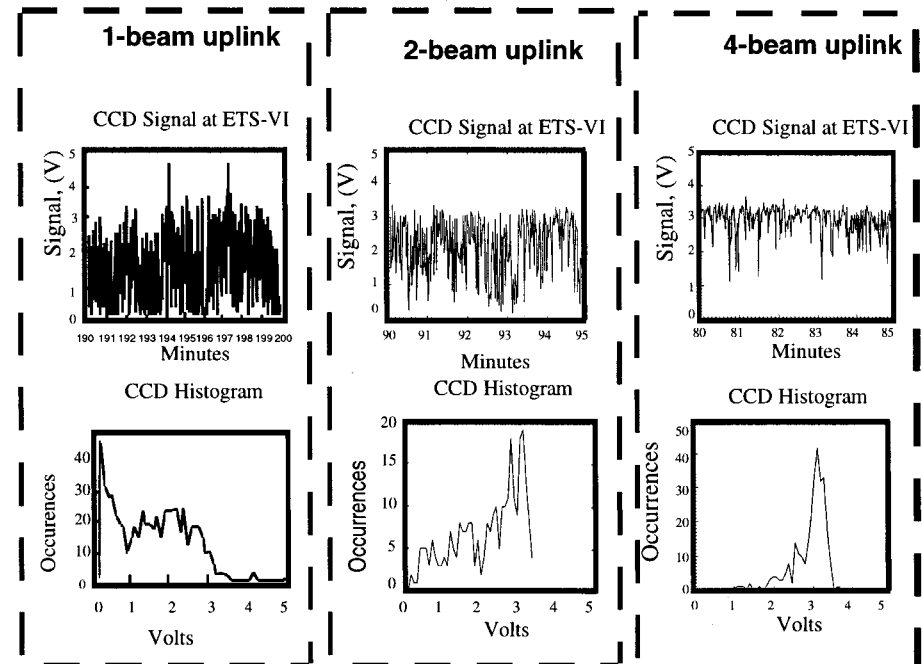


GOLD Multiple-beam Transmission

- Multiple beam uplink mitigates effects of atmospheric scintillation and beam wander
 - Beams are propagated through different atmospheric coherent cells
 - Each beam is delayed relative to the other by greater than laser's coherence length

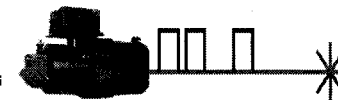


TMF 0.6-m Transmitter Telescope

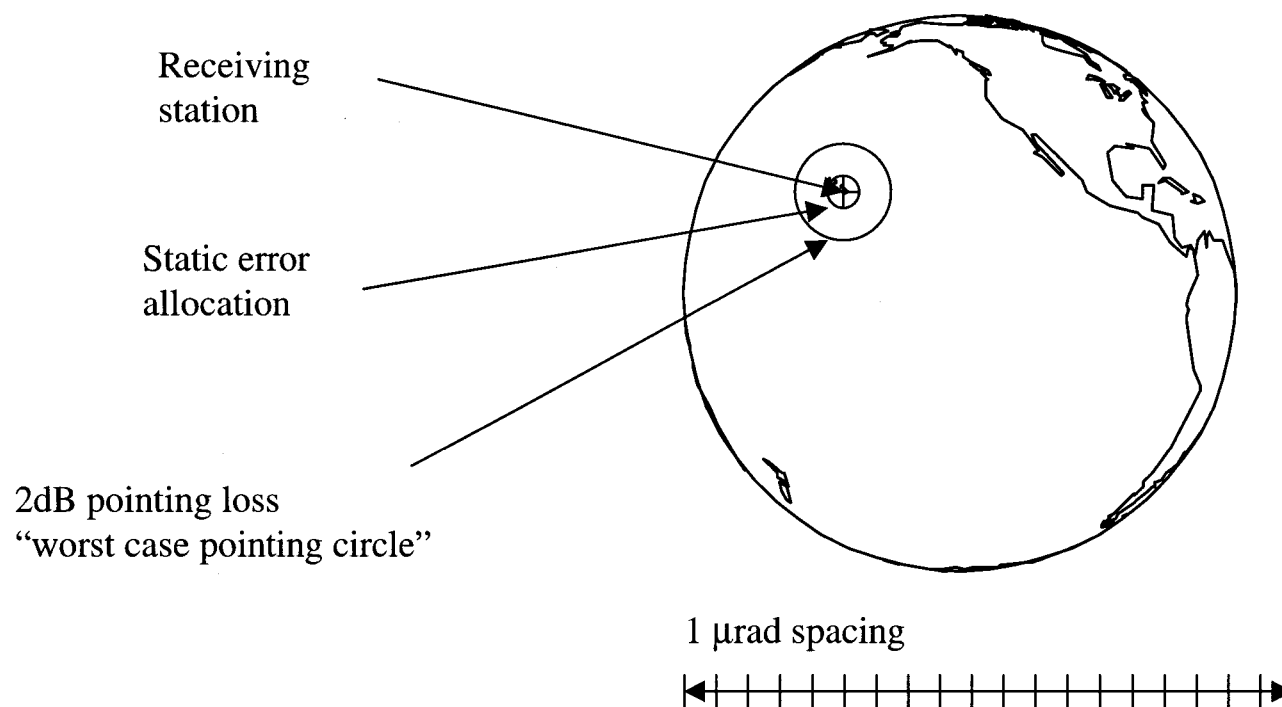




Beam Pointing Requirements



- Several μrad vs. $0.1 \sim 0.5$ degrees (RF)



< Diagram illustrating the pointing requirements for the Europa orbiter mission >



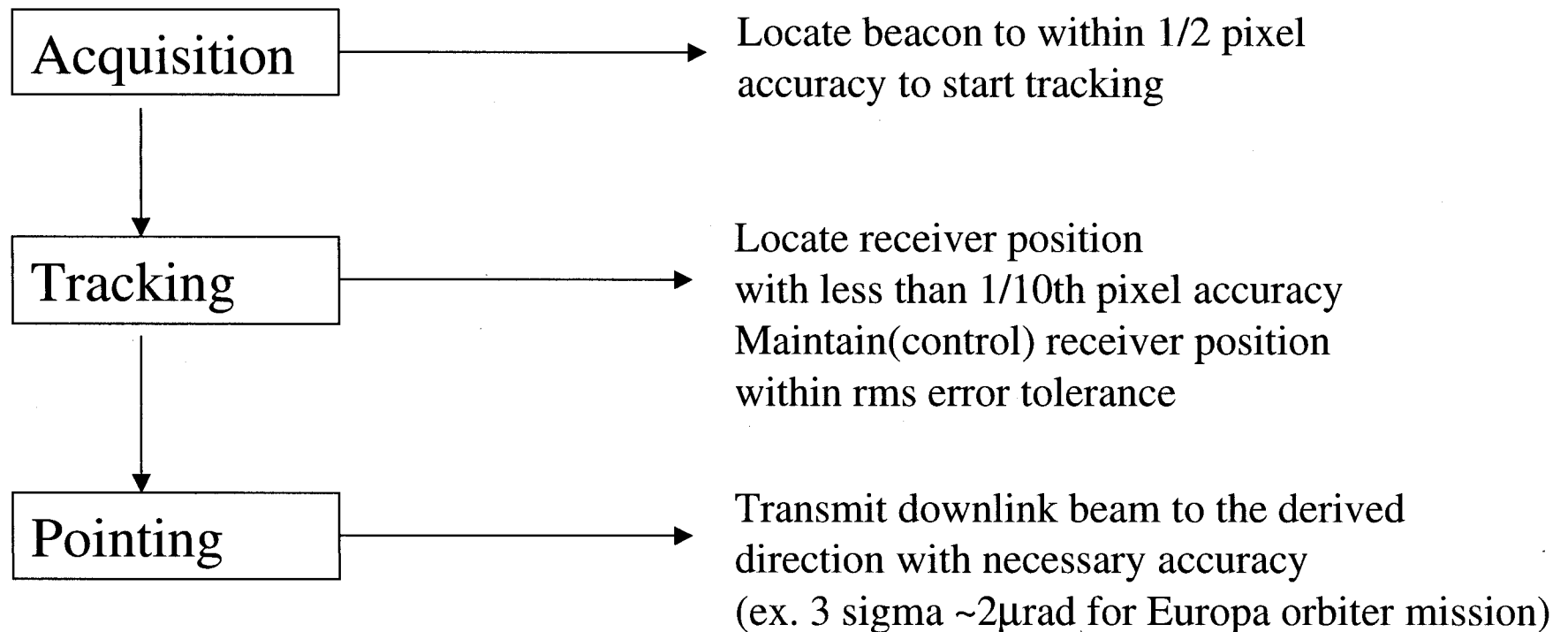
Approaches for Accurate Tracking/Pointing



- S/C does not provide accurate receiver position
- Various sources (uplink laser, Earth, Moon, Star) may be used as beacon.
- Need advanced FPA (Focal Plane Array) with high QE (Quantum Efficiency) and large field of view
- Increase tracking bandwidth
- Decrease the transmission of S/C vibration
- Different ATP strategies are necessary to fully exploit various beacon sources

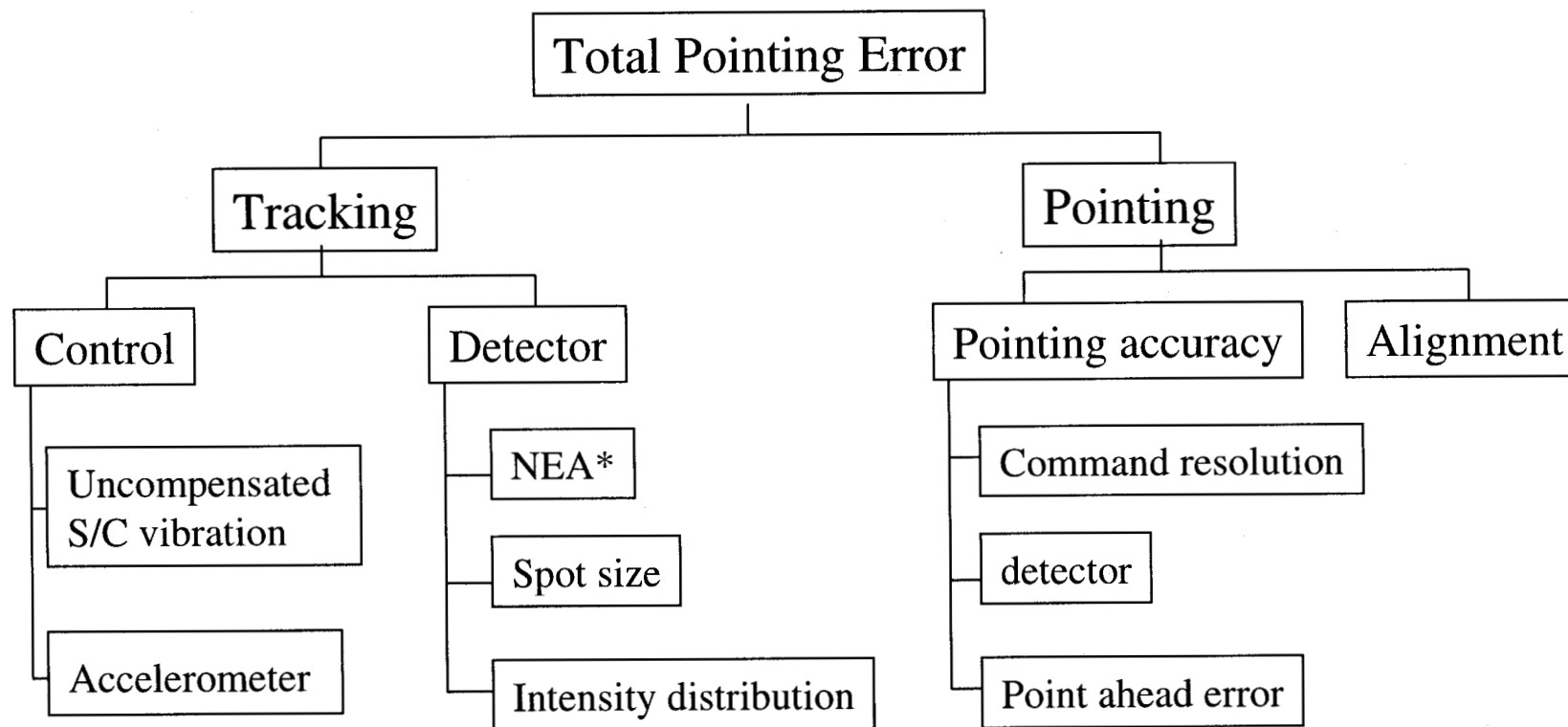


Principal of Operations





Sources of Tracking and Pointing Errors



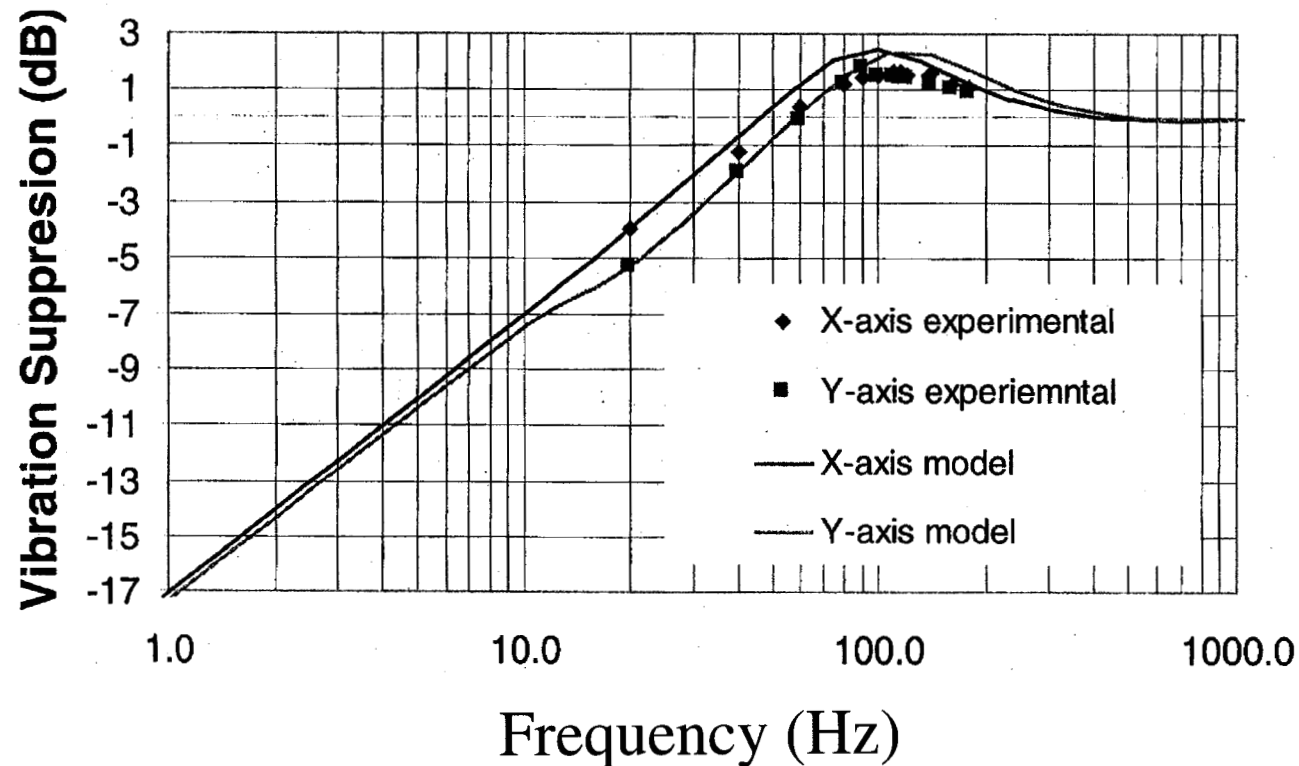
NEA* : Noise Equivalent Angle of tracking detector



Lab OCD: Fine Tracking

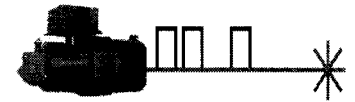


- Vibration suppression bandwidth $\sim 50\text{Hz}$ in both axes

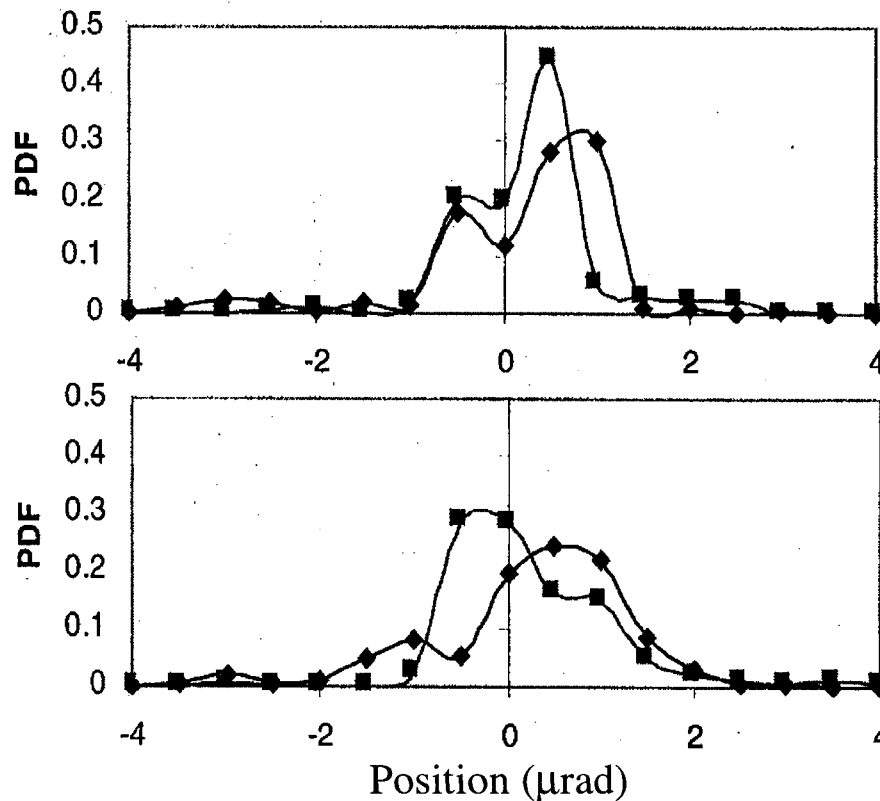




Lab OCD: Centroiding Accuracy



- Centroiding accuracy ~ one-tenth of a pixel



Laser/reference Centroid

$$\sigma_x = 1.10 \mu\text{rad}$$

$$\sigma_y = 1.10 \mu\text{rad}$$

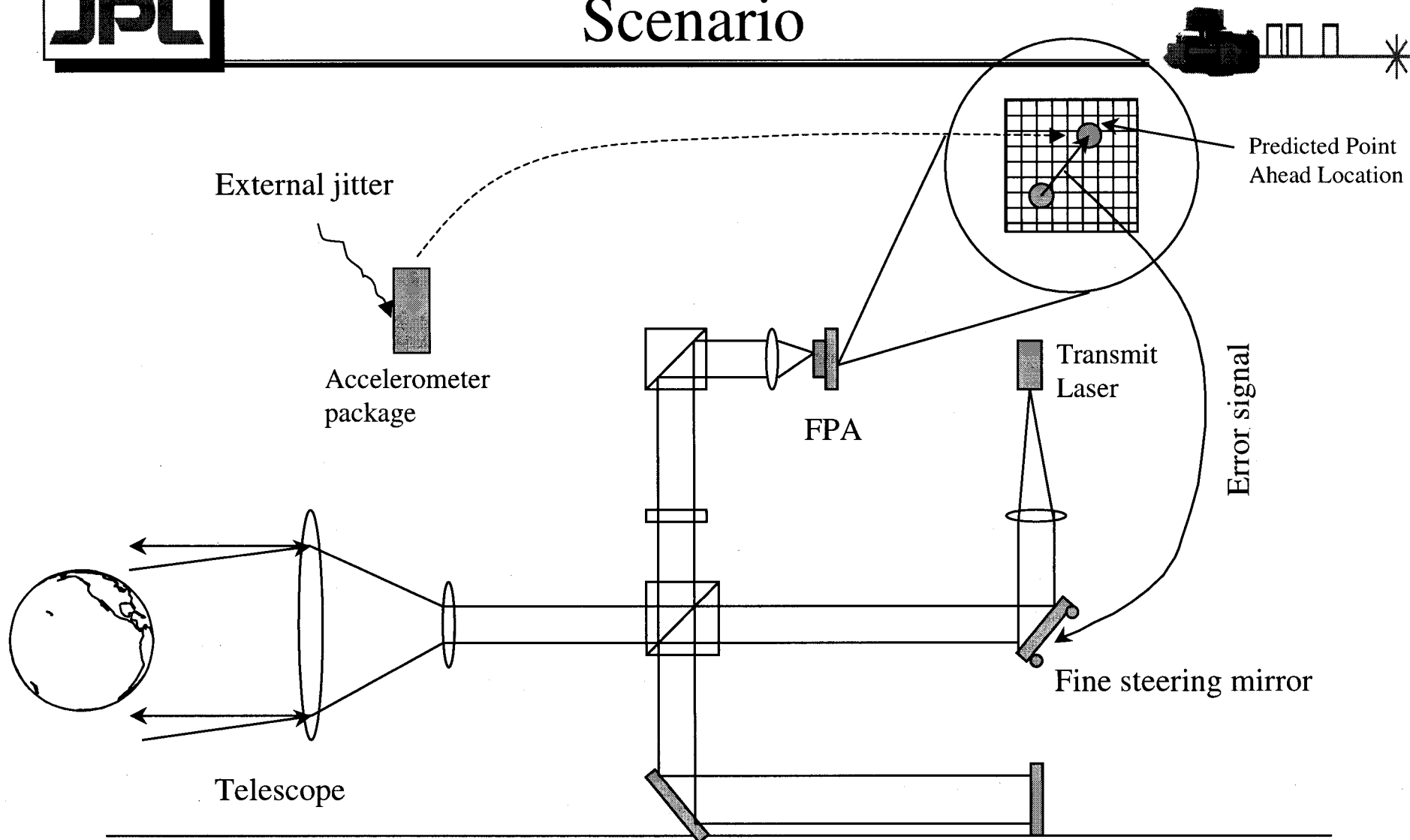
Beacon Centroid

$$\sigma_x = 1.12 \mu\text{rad}$$

$$\sigma_y = 0.84 \mu\text{rad}$$

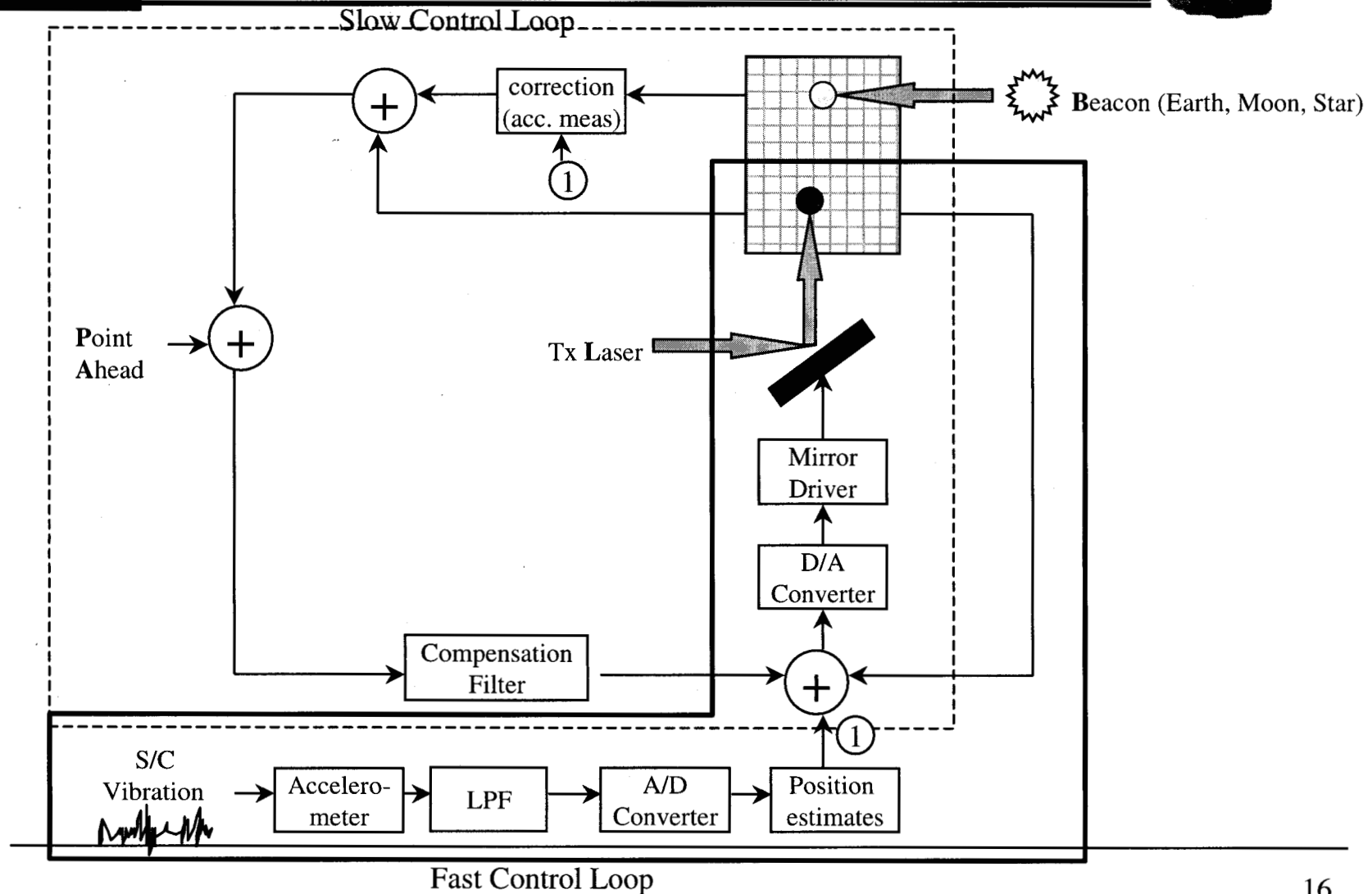
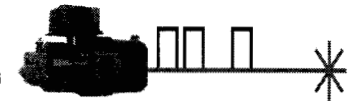


Acquisition/Tracking/Pointing Scenario



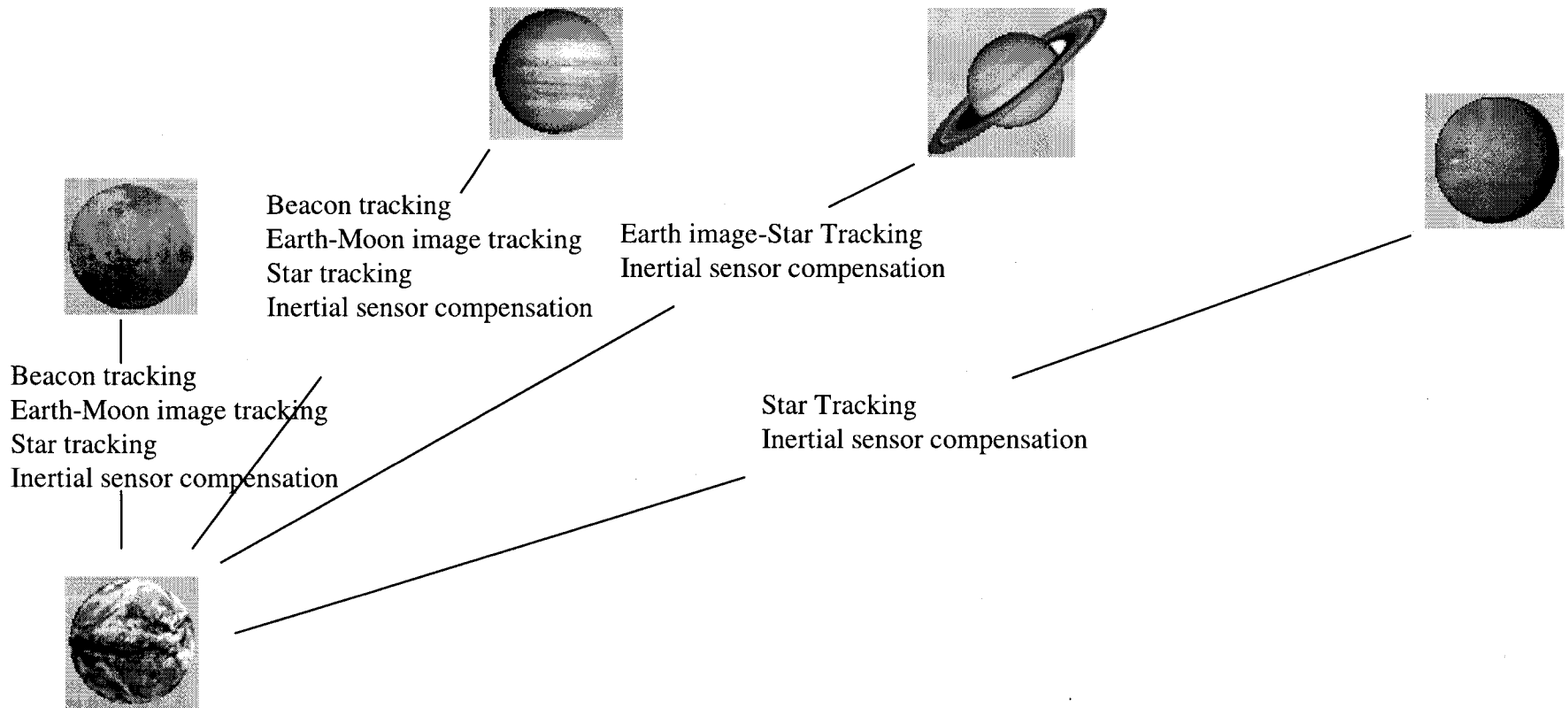


Acquisition/Tracking/Pointing Control Loop



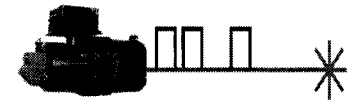


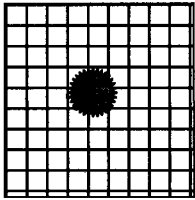
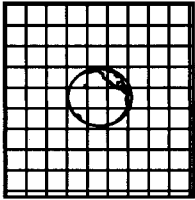
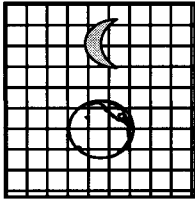
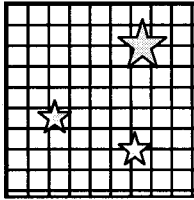
ATP Technologies for Deep Space Missions





Comparison of Various Tracking Approaches



	Uplink Beacon tracking	Earth tracking only	Earth-Moon tracking	Star tracking only
				
Req.'s	Uplink signal	calibration for albedo variations	predictable albedo Moon requires 40x integration time	FOV, inertial sensor, straylight rejection
Limitation	Only applicable at close w/o inertial sensor	Signal varies w/ distance, phase angle	Signal varies w/ distance, phase angle	Low signal 10-20Hz for 10 th mag. stars
S/C attitude for track	Yes	Yes	Yes	No
High Earth signal	No	Yes	Yes	No
Inertial sensors	Not near to Earth	@High phase angles	@High phase angles Long exposure (Moon)	Yes



Key Technology Developments



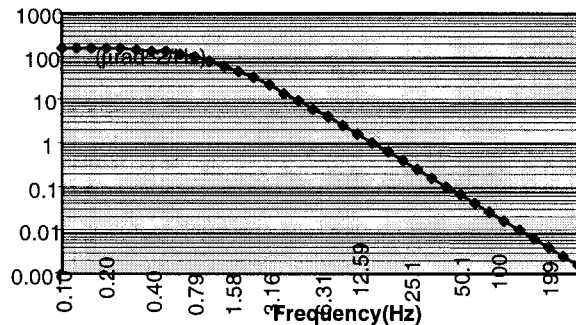
- **Vibration Isolation** - dominant source to mispointing, especially high frequency vibration
- **Inertial Sensor** - increases tracking bandwidth
- **Extended Source Image Acquisition Algorithm** - Earth, Moon image can be used as beacon source
- **Star Tracking** - stars are attractive beacon sources beyond 10AU
- **Fast Steering Mirror (FSM)** - increases tracking bandwidth
- **Focal Plane Array (FPA)** - determines pointing accuracy



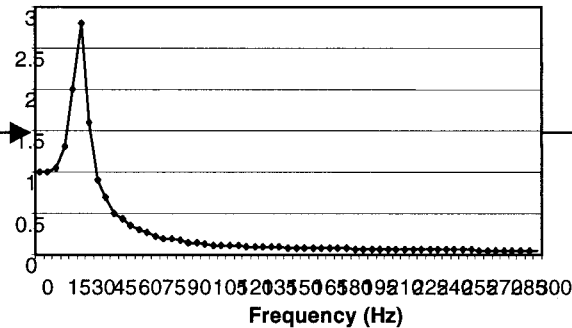
Technology Developments - Vibration Isolation



- Passive isolator - cost effective and efficient method to improve tracking capability by reducing transmission of high frequency S/C vibration

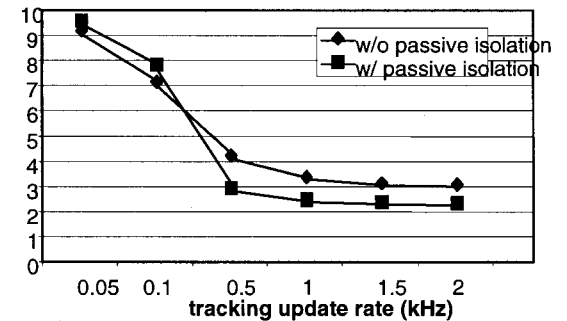


Olympus S/C vibration power spectral density



Passive isolator
Lord HTOP-5

OCD tracking
system



Uncompensated, S/C vibration
induced tracking error

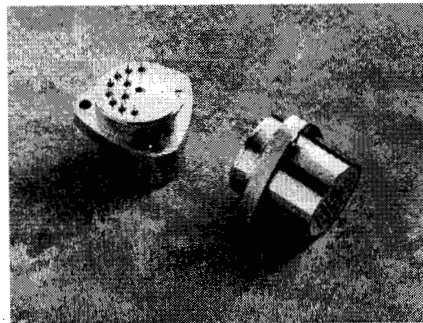
- Tracking error can be reduced by 20~30%



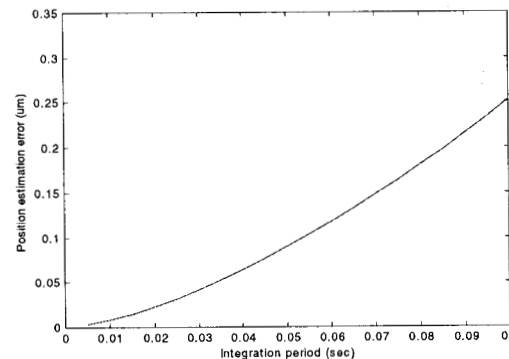
Technology Developments - Inertial sensor



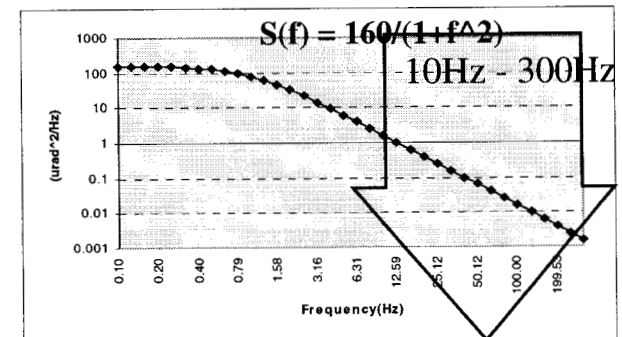
- S/C vibration causes random disturbance along telescope bore-sight
- Weak beacon signal -> slow FPA update -> poor tracking capability
- Inertial sensor can compensate slow FPA update by measuring S/C vibration between FPA updates
- **Key parameters** - S/C position estimation error due to **sensor rms noise & calibration error**



Picture of QA-3000 accelerometer
rms noise - $76\mu\text{g}$
calibration error - 0.5%



Position estimation error for rms noise of $100\mu\text{g}$ and sampling of 5kHz

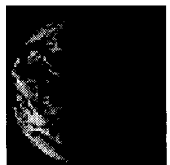
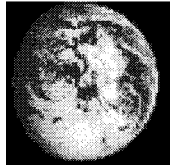


rms jitter of $4\mu\text{rad}$

Calibration error should be better than 2.5% for integration time of 0.1 sec. and error budget of $0.1\mu\text{rad}$ given Olympus S/C base motion PSD.



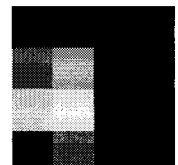
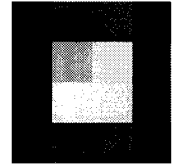
Technology Developments - Image acquisition



Estimation of receiver location from extended source

Estimation of geometric center
of extended source

Known offset from receiver to
geo-center



Acquisition algorithms - sensitive to albedo variations and background noise

- Correlation method
- Edge detection method

Albedo offset calibration -

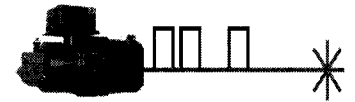
Moon image can be used to calibrate due to its known albedo

Accuracy improvements - Multiple, sequential images with edge detection

yielded 1/40th pixel accuracy in simulations



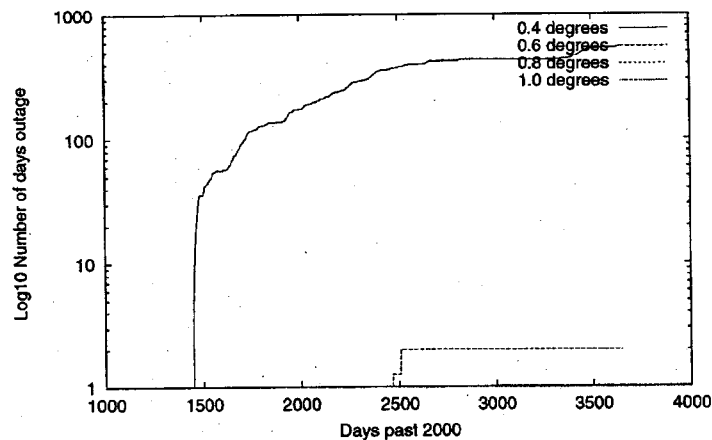
Technology Developments - Star Tracking



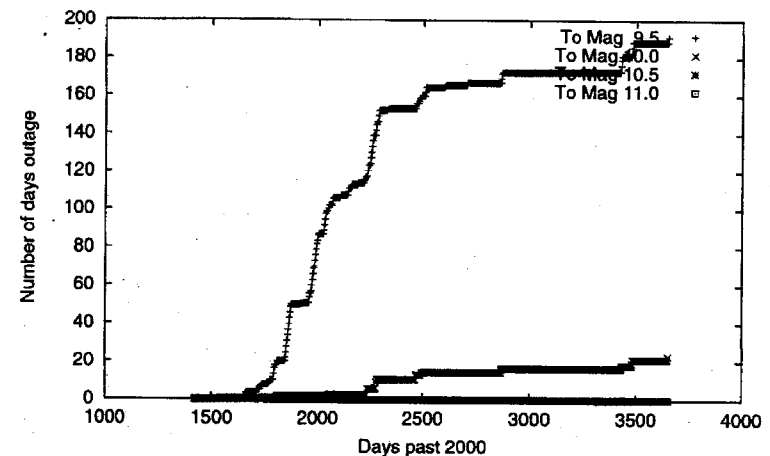
- Key parameters - signal level, star coverage

Star Magnitude	Flux with no optical loss	Flux with 25% system efficiency	Number of frames/sec. For accurate centroiding
7.5	1.0E6	250,000	25 to 50
10.0	1.0E5	25,000	5 to 10
11.0	4.0E4	10,000	1 or 2

< Signal strength from stars of different magnitudes >



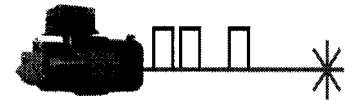
Number of days with less than 5 stars and
a limiting magnitude of 11



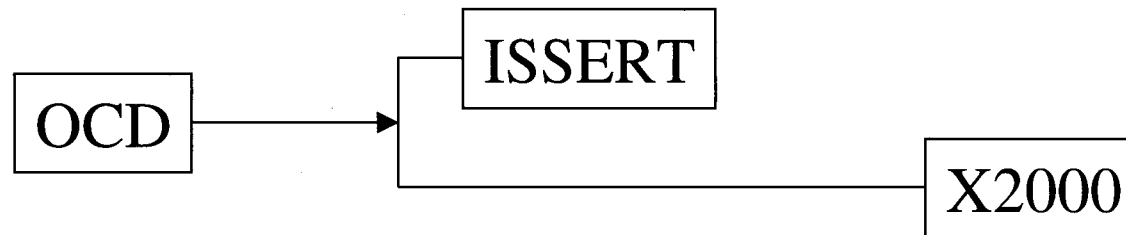
Number of days with less than 2 stars within
0.6 degrees of Earth as seen from Jupiter



Technology Developments - Fast Steering Mirror

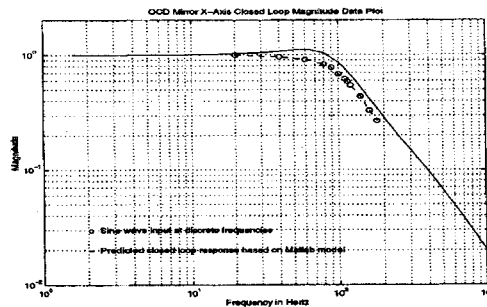


FSM determines vibration rejection capability of tracking control system



General Scanning Tabs II mirror

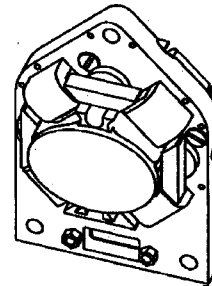
Travel $\pm 25\text{mrad}$
Resonance $17/19\text{Hz}$
frequency



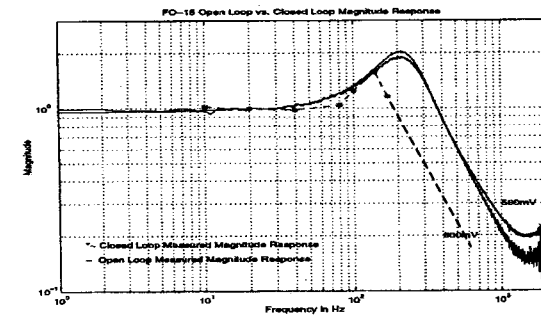
3dB @ 120Hz

LHD FO15 mirror

$\pm 44\text{mrad}$
 $205/270\text{Hz}$



FO15



3dB @ $>200\text{Hz}$



Technology Developments - Focal Plane Array



Format	128x128	512x512	1024x1024
Pixel size	16μm	12μm	10-20μm
Bits/pixel	8bits	10bits	>12bits
Frame update rate	2kHz	2kHz	>500Hz
Centroiding accuracy	1/10 th pixel	<1/10 th pixel	< 1/20 th pixel



Summary



- Narrow laser transmit beam imposes many technical challenges in beam pointing
- S/C vibration is the dominant source to beam mispointing
- Bright beacon signal (Uplink laser, Earth, Moon, Stars) is necessary to maintain receiver position within few μrad under S/C vibration
- Scattered sun light is a major consideration for dim beacon signal
- Various ATP strategies are required to successfully address the need for deep space optical communication